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WPB FOR SOLAR SUPREMACY SATELLITE (SSS) BY MICROWAVE POWER TRANSMISSION (MPT) ANTENNAS

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ABSTRACT

In this paper the basic operation and principle of Space Solar Power Satellite is described. The microwave power transmission antennas are suitable for future application of solar power satellite. By use of magnetron & semiconductor amplifier the efficiency of microwave power transmitter can be enhanced. The microwave energy transmitter and receivers are the main focus in this paper. After a several experiment and theoretical discussion we identified a suitable MPT with specific parameters for wireless power broadcast system.

KEYWORDS: Wireless Power Broadcast (WPB), Space Solar Power Satellite (SPS), Microwave Power Transmission Antennas (MPTA), Magnetron, Compact Microwave Energy Transmitter (COMET), HEMT

INTRODUCTION

It is known that electromagnetic energy also associated with the propagation of theelectromagnetic waves. We can use theoretically all electromagnetic waves for a wireless powerbroadcast (WPB). The difference between the WPB and communication systems is only efficiency.The Maxwell's Equations indicate that the electromagnetic field and its power diffuse to alldirections. Although we transmit the energy in the communication system, the transmitted energy isdiffused to all directions. Although the received power is enough for a transmission of information, the efficiency from the transmitter to receiver is quiet low. Therefore, we do not call it the WPB system.

Typical WPB is a point-to-point power transmission. For the WPB, we had better concentrate power to receiver. It was proved that the power transmission efficiency can approach close to 100%.We can more concentrate the transmitted microwave power to the receiver aperture areas with tapermethod of the transmitting antenna power distribution. Famous power tapers of the transmittingantenna are Gaussian taper, Taylor distribution, and Chebychev distribution. These taper of thetransmitting antenna is commonly used for suppression of side lobes. It corresponds to increase thepower transmission efficiency. Concerning the power transmission efficiency of the WPT, there aresome good optical approaches in Russia.

Future suitable and largest application of the WPB via microwave is a Space Solar PowerSatellite (SPS). The SPS is a gigantic satellite designed as an electric power plant orbiting in theGeostationary Earth Orbit (GEO). It consists of mainly three segments; solar energy collector toconvert the solar energy into DC (direct current) electricity, DC-to-micro wave converter, and large antenna array to beam down the microwave power to the ground. The first solar collector can beeither photovoltaic cells or solar thermal turbine.

The second DC-to-microwave converter of the SPScan be either microwave tube system and/or semiconductor system. It may be their combination. The third segment is a gigantic antenna array. An amplitude taper on the transmitting

antenna is adopted in orderto increase the beam collection efficiency and to decrease side lobe level in almost all SPS design. Atypical amplitude taper is called 10 dB Gaussian in which the power density in the center of thetransmitting antenna is ten times larger than that on the edge of the transmitting antenna.

The SPS is expected to realize around 2030. Before the realization of the SPS, we can consider theother application of the WPT. In resent years, mobile devices advance quickly and requiredecreasing power consumption. It means that we can use the diffused weak microwave power as apower source of the mobile devices with low power consumption such as RF-ID. The RF-ID is a radio IC-tug with wireless power transmission and wireless information.

ANTENNAS FOR MICROWAVE POWER TRANSMISSION

All antennas can be applied for both the MPT system and communication system, for example, Yagi-Uda antenna, horn antenna, parabolic antenna, micro strip antenna, phased array antenna or anyother type of antenna. To fixed target of the MPT system, we usually select a large parabolic antenna, for example, in MPT demonstration in 1975 at the Venus Site of JPL Goldstone Facility and inground-to-ground MPT experiment in 1994-95 in Japan (See Figure 1 and Figure 2). In the fuel-freeairship light experiment with MPT in 1995 in Japan, they changed a direction of the parabolicantenna to chase the moving airship.

Figure 1: MPT Laboratory Experiment in 1975 by W. Brown

Figure 2: SPS Demonstrator "SPRITZ" with 5.8 GHz Experiment in Japan in 1994-95

However, we have to use a phased array antenna for the MPT from/to moving transmitter/receiverwhich include the SPS because we have to control a microwave beam direction accurately andspeedy. The phased array is a directive antenna which generate a beam form whose shape anddirection by the relative phases and amplitudes of the waves at the

individual antenna elements. It ispossible to steer the direction of the microwave beam. The antenna elements might be dipoles, slot antennas, or any other type of antenna, even parabolic antennas. In some MPT experiments in Japan, the phased array antenna was adopted to steer a direction of the microwave beam (Figure 3). All SPS is designed with the phased array antenna. We consider the phased array antenna for allfollowing MPT system.

Figure 3: Phased Array Used in Japanese Field MPT Experiment (Left: for MILAX in 1992, Right: for SPRITZ in 2000)

RECENT TECHNOLOGIES FOR TRANSMITTERS

The technology employed for the generation of microwave radiation is an extremely important subject for the MPT system. We need higher efficient generator/amplifier for the MPT system thanthat for the wireless communication system. For highly efficient beam collection on rectenna array, we need higher stabilized and accurate phase and amplitude of microwave when we use phased arraysystem for the MPT.

There are two types of microwave generators/amplifiers. One is a microwave tube and the other is asemiconductor amplifier. Trew reviewed microwave generators/amplifiers, frequency vs. averaged power as shown in Figure 4. These have electric characteristics contrary to each other. Themicrowave tube, such as a cooker-type magnetron, can generate and amplify high power microwave (over kW) with a high voltage (over kV) imposed. Especially, magnetron is very economical. Thesemiconductor amplifier generate low power microwave (below 100W) with a low voltage (below fifteen volt) imposed. It is still expensive currently. Although there are some discussions concerninggeneration/amplifier efficiency, the microwave tube has higher efficiency (over 70%) and thesemiconductor has lower efficiency (below 50%) in general. We have to choose tube/semiconductorcase by case for the MPT system.

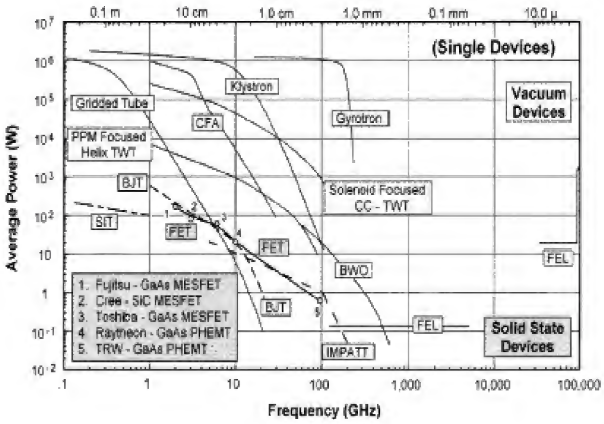

Figure 4: Average RF Output Power versus Frequency for Various Electronic Devices and Semiconductors

MAGNETRON

Magnetron is a crossed field tube in which *E X B*forces electrons emitted from the cathode totake cyclonical path to the anode. The magnetron is self-oscillatory device in which the anodecontains a resonant RF structure. The magnetron has long history from invention by A. W. Hull in1921. The practical and efficient magnetron tube gathered world interest only after K. Okabe proposed the divided anode-type magnetron in 1928. Magnetron technologies were advanced duringthe World War II, especially in Japanese Army. The magnetrons main were advanced andmanufactured for the microwave ovens. As a result, the magnetron of 500 – 1,000 W is widely usedin microwave ovens in 2.45 GHz, and is a relatively inexpensive oscillator (below $5). There is a netglobal capacity of 45.5GW/year for all magnetrons used in microwave ovens whose production is 50– 55 millions.

A history of the magnetron is a history of a microwave oven. The first microwaveoven with a magnetron sold shortly in U. S. A. after the World War II ended for more than $2, 000, the equivalent of about $20,000 today. In 1960's, Japan played a important role to reduce the cost ofthe microwave oven. Compared that American tube's cost was $300 and they planned to sell for$500 in 1960's, Japanese tube cost was less than $25. In 1970, U.S. manufacturers sold 40,000 ovensat $300 to $400 apiece, but by 1971 the Japanese had begun exporting low-cost models priced $100to $200 less. Sales increased rapidly over the next 15 years, rising to a million by 1975 and 10million by 1985, nearly all of them Japanese. But history repeats itself. Instead of Japanesemicrowave oven, Korean and Chinese more reduce the cost of the microwave oven now.

Therefore, the magnetron is suitable device for the MPT because of high efficiency and low costand unsuitable device because of its unstable frequency and uncontrollable phase. If we do not makea phased array to control beam direction electrically, the magnetron can be applied for the MPTsystem. However, the cooker-type magnetron itself cannot be applied for the phased array-type MPTbecause it is only a generator and we cannot control/stabilize the phase and the amplitude. Thecooker-type magnetron was considered as noisy device. It is however confirmed that spuriousemissions from the cooker-type magnetron with a stable DC power supply is low enough and thiscan be applied to the MPT system. Peak levels of higher harmonics are below -60 dBc and otherspurious is below -100 dBc.It was W. C. Brown who invented a voltage controlled oscillator with a cooker-type magnetron ina phase locked loop. He could control and stabilize a phase of microwave emitted fromcooker-type magnetron. In present, some research groups try and succeed to develop new magnetron.

Figure 5: Phased Array with 2.45GHz Phase Controlled Magnetrons Developed in Kyoto University

SEMICONDUCTOR AMPLIFIER

After 1980s, semiconductor device plays the lead in microwave world instead of the microwavetubes. It causes by

advance of mobile phone network. The semiconductor device is expected toexpand microwave applications, for instance, phased array and Active integrated antenna (AIA), because of its manageability and mass productivity. After 1990s, some MPT experiments werecarried out in Japan with phased array of semiconductor amplifiers.

Typical semiconductor device for microwave circuits are FET (Field Effect Transistor), HBT (Hetero junction Bipolar Transistor), and HEMT (High Electron Mobility Transistor). Presentmaterials for the semiconductor device are Si for lower frequency below a few GHz and Ga As for higher frequency. We design microwave circuits with these semiconductor devices. It is easy tocontrol a phase and amplitude through the microwave circuits with semiconductor devices, forexample, amplifiers, phase shifters, modulators, and so on. For the microwave amplifiers, circuitdesign theoretically determines efficiency and gain. A, B, C class amplifiers are classified in biasvoltage in device. These classes are also applied in kHz systems. In D, E, F class amplifiers formicrowave frequency, higher harmonics are used effectively to increase efficiency, theoretically100%. Especially F class amplifier is expected as high efficient amplifier for the MPT system.

We always have to consider the efficiency. Some reports noted that it is possible to realize a PAE (power added efficiency = (Pout-Pin)/PDC) of 54%, efficiency of about 60%, at 5.8GHz. These are champion data in laboratory. To develop the high efficient amplifier, we need strict adjustment incontrary of mass productivity. It causes that the semiconductor amplifiers keep expensive cost forthe MPT system. It potentially has low price capability by the mass production. An efficiency of adriver stage is also taken into consideration if the gain of the final stage is not enough.

The other requirement from MPT use to the semiconductor amplifier is linearity of amplifierbecause power level of the MPT is much higher than that for wireless communication system and wehave to suppress unexpected spurious radiation to reduce interference. The maximum efficiencyusually is realized at saturated bias voltage. It does not guarantee the linearity between input andoutput microwaves and non-linearity causes high spurious which must be suppressed in the MPT.Therefore, dissolution of tortuous relationship between efficiency and linearity is expected by theMPT.

There are unique development items for the SPS from the microwave point of view distinguishedfrom the ordinary use of the microwave technology such as telecommunications. These three pointsmay be described as 1) pureness in spectrum, 2) high power and high efficient power generation andhigh efficient detector in a small and light fashion, and 3) precise beam control for a large phasedarray antenna combining with a huge number of sub-arrays.

To cope with the second requirement for the microwave technology, the large plate model by alayered configuration in a sandwich fashion was proposed. The point of this configuration is the effective integration with DC power generation, microwave circuit operation and radiation, and theircontrol. As one of the promising microwave technologies, the “the Active Integrated Antenna (AIA)” technique is considered. The AIA is defined as the single entity consisting of an integratedcircuit and a planar antenna. The AIA has many features applicable to the SPS. Due to the natureof small-size, thinness, lightness and multi-functions in AIA, a power transmission part of the spacetenna (space antenna) can be realized in thin structure. Prof. Kawasaki’s group have developedsome AIA system for the MPT application [20].

In present, new materials are developed fore the semiconductor device to increased output powerand efficiency. They are called wide-band gap devices such as SiC and GaN. The wide-band gap devices can make over hundreds watt amplifier with one chip. In recent days, there are somedevelopment of microwave amplifiers with SiC MESFET or GaN

HEMT. The othertrend is development of MMIC (Microwave Monolithic Integrated Circuit) to reduce space andweight, especially for mobile applications. Lighter transmitters can be realized with the MMICdevices. The MMIC devices still have heat-release problems, poor efficiency, and low power output.However, it is expected that the technical problems will be solved by efforts of many engineers.

MICROWAVE ENERGY TRANSMITTER

Largest MPT application is a SPS in which over GW microwave will be transmitted from space toground at distance of 36,000km. In the SPS, we will use microwave transmitters in space. For spaceuse, the microwave transmitter will be required lightness to reduce launch cost and higher efficiencyto reduce heat problem.

A weight of the microwave tube is lighter than that of the semiconductor amplifier when wecompare the weight by power-weight ratio (kg/kW). The microwave tube can generate/amplify higher power microwave than that by the semiconductor amplifier. Kyoto University's group have developed a light weight phase controlled magnetron called COMET, Compact Microwave Energy Transmitter with a power-weight ratio below 25g/W (figure 6). The COMET includes a DC/DC converter, a control circuit of the phase controlled magnetron with 5.8 GHz, a heat radiation circuit,a wave guide, and an antenna. The power-weight ratio of the COMET is lightest weight in allmicrowave generators and amplifiers. TWTA for satellite use has lighter power weight ratio: 220Wat 2.45GHz at 2.65 kg (the TWTA weighs 1.5kg, the power supply weighs 1.15kg). 130W at 5.8GHz at 2.15 kg (the TWTA weighs 0.8kg, the power supply weighs 1.35kg). Hence, they can deliver12g/W and 16.5g/W, respectively.

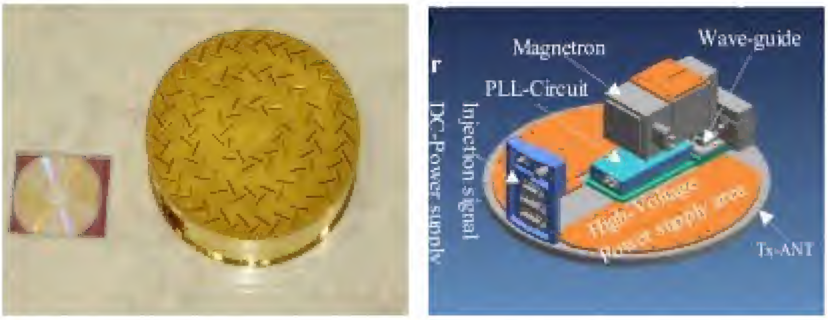

Figure 6: Compact Microwave Energy Transmitter with the PCM (COMET)

They do not include a heat radiation circuit, a wave guide, andan antenna. The semiconductor amplifier is not light remarkably. Examples of characteristics ofvarious transmitters for space use are shown in Table 1. Although it may seem that semiconductoramplifiers are light in weight, they have heavy power-weight ratio because output microwave poweris very small.

Table 1: Characteristics of Semiconductor Amplifier for Space Use

Satellite	ETS-6	TDRSS	NSTAR	INT-7	JCSAT-3
Efficiency	31%	32%	36%	29%	40%
Output	14W	24W	40W	30W	34W
Weight	1.2kg = 85g/W	3.4kg =121g/W	2.5kg =63g/W	1.7kg =57g/W	1.9kg =56g/W
Frequency	2.5GHz	2GHz	2.5GHz	4GHz	4GHz

Heat reduction is most important problem in space. All lost power converts to heat. We needspecial heat reduction system in space. If we use high efficient microwave transmitters, we canreduce weight of heat reduction system. We should aim for over 80 % efficiency for the microwavetransmitter, which must include all loss in phase shifters,

isolators, antennas, power circuits.Especially, the SPS is a power station in space, therefore, heat reduction will be a seriousproblem.

MICROWAVE ENERGY RECEIVER

Point-to-point MPT system needs a large receiving area with a rectenna array because onerectenna element receives and creates only a few W. Especially for the SPS, we need ahuge rectenna site and a power network connected to the existing power networks onthe ground. On contrary, there are some MPT applications with one small rectennaelement such as RF-ID.

The word “rectenna” is composed of “rectifying circuit” and “antenna”. The rectenna and its wordwere invented by W. C. Brown in 1960’s. The rectenna can receive and rectify a microwavepower to DC. The rectenna is passive element with a rectifying diode, operated without any powersource. There are many researches of the rectenna elements (Figure 7). Famous research groups of therectenna are Texas A&M University in USA, NICT (National Institute of Information and Communications Technology, past CRL) in Japan, and Kyoto University in Japan. The antenna of rectenna can be any type such as dipole, Yagi-Uda antenna, micro strip antenna, monopole, loop antenna, coplanar patch, spiral antenna, or even parabolic antenna. The rectenna can also take any type of rectifyingcircuit such as single shunt full-wave rectifier, full-wave bridge rectifier, or other hybrid rectifiers. The circuit, especially diode, mainly determinesthe RF-DC conversion efficiency. Silicon Schottky barrier diodes were usually used for the previousrectennas. New diode devices like SiC and GaN are expected to increase the efficiency. Therectennas with FET or HEMT appear in recent years. The rectenna using the active devicesis not passive element.

The single shunt full-wave rectifier is always used for the rectenna. It consists of a diode inserted to the circuit in parallel, a λ/4 distributed line, and a capacitor inserted in parallel. In an ideal situation, 100% of the received microwave power should be converted into DC power. Its operation can be explained theoretically by the same way of a F-class microwave amplifier. The λ/4 distributed line and the capacitor allow only even harmonics to flow to the load. As a result, the wave form on the λ/4 distributed line has a π cycle, which means the wave form is a full-wave rectified sine form. The world record of the RF-DC conversion efficiency among developed rectennas is approximately 90% at 4W input of 2.45 GHz microwave. Other rectennas in the world have approximately 70 – 90 % at 2.45GHz or 5.8GHz microwave input. The RF-DC conversion efficiency of the rectenna with a diode depends on the microwave power input intensity and the connected load. It has the optimum microwave power input intensity and the optimum load to achieve maximum efficiency. When the power or load is not matched the optimum, the efficiency becomes quite low (Figure 7). The characteristic is determined by the characteristic ofthe diode. The diode has its own junction voltage and breakdown voltage. If the input voltage to thediode is lower than the junction voltage or is higher than the breakdown voltage, the diode does notshow a rectifying characteristic. As a result, the RF-DC conversion efficiency drops with a lower orhigher input than the optimum.

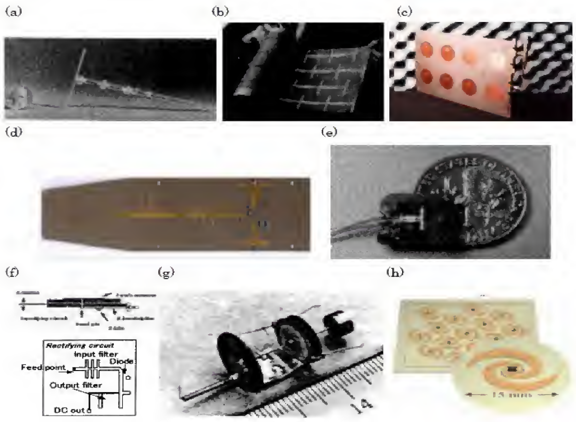

Figure 7: Various Rectennas (a) Brown's Rectenna (2.45GHz), (b) Brown's Thin-Film Rectenna (2.45GHz), (c) Hokkaido University's Rectenna (2.45GHz), (d) Kyoto University's Rectenna (2.45GHz) (e) Texas A&M University's Rectenna (35GHz), (f) CRL's Rectenna (5.8GHz), (g) Denso's Rectenna for Micro Robot (14-14.5GHz), (h) University of Colorado's Rectenna (8.5-12.2GHz)

CONCLUSIONS & FUTURE WORK

In recent years, major research topic in the rectenna is to research and develop new rectennaswhich are suitable for a weak-wave microwave, which can be used in experimental power satellitesand RF-ID. The weak-wave means in the "micro-watt" range. The RF-ID is the first commercialMPT system in the world. The weak microwave will be transmitted from the experimental satellite on LEO to the ground because microwave power and size of transmitting antenna on theexperimental satellite will be limited by the capacity of the present launch rockets. We have twoapproaches to increase the efficiency at the weak microwave input. One is to increase an antennaaperture under a weak microwave density. There are two problems for this approach. Itmakes sharp directivity and it is only applied for the SPS satellite experiment and not for the RF-IDapplication. The other approach is to develop a new rectifying circuit to increase the efficiency at a weak microwave input. We can apply this type of the rectenna for the commercial RF-ID.

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